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ANALYSIS OF SWITCHING DUTY EXPECTED ON HIGH-SPEED 500 kV SF6 DISCONNECTS AT BOWMANVILLE SS

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Analytical studies and computer simulations were performed to predict the duty imposed on 500-kV SF6 disconnects when switching Darlington NGS station service transformers off potential. The results show that the disconnects may be required to interrupt transformer inrush currents approaching 20 A peak, which is considerably more severe than the specified levels of 4 A inductive or 1 A capacitive current. Since there is no evidence that the disconnects are capable of this more severe duty, it is recommended that the switch manufacturer be consulted before a decision is made to use the disconnects as planned.

1. INTRODUCTION

Bowmanville SS is a Gas Insulated Station (GIS) located less than a kilometre from Darlington NGS. High-speed SF6 disconnects are provided at Bowmanville SS on each of four circuits supplying the Station Service Transformers (SST) at Darlington NGS. It was intended that these disconnects would provide a means of switching the SSTs off potential without de-energizing the respective GIS bus. Accordingly Siemens, the switch manufacturer, was quoted a switching requirement of 4 A magnetizing current. This duty was subsequently revised to 1 A capacitive current/1/.

The device supplied by Siemens is essentially a conventional SF6 disconnect modified to achieve a faster contact opening speed. It has apparently been designed specifically for Bowmanville SS, hence there is no prior operating experience available with the device to gauge its performance. Siemens has conducted tests on a single-pole unit while interrupting up to 8 A rms inductive current at a recovery voltage of 280 kV rms across the pole, 140 kV line to ground on each side/2,3/. However this test configuration does not correspond sufficiently to either of the specified duties, nor does it match the circuit configuration in the intended application/4,5/. Nevertheless Siemens expressed confidence in the device/6,7,8/, and a decision was made to conduct full-scale switching tests on one three-phase unit on site. We were asked by Darlington Engineering to plan and to carry out suitable full-scale switching tests/1/.

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In preparation for these tests, analytical studies and computer simulations were performed to quantify the switching duty expected in this application. Results of our analysis suggest that the interrupting duty imposed on the disconnect is considerably more severe than the above specified levels. While we are unable to predict the switching performance with certainty, it seems possible that the device could incur prolonged arcing, possibly leading to a flashover to the GIS enclosure. The planned switching tests have therefore been postponed indefinitely pending consultation with the manufacturer. Consideration is also being given to using the disconnects only for providing electrical isolation for the respective circuits./9/.

This report documents our analysis and our concerns regarding the use of this disconnect in this application.

2. ELECTRICAL ARRANGEMENT

The circuit supplying each of the SSTs is similar, therefore our findings are applicable to all four high-speed disconnects at Bowmanville SS. Present discussion is restricted to the circuit supplying SST1 (Figure 1). The circuit consists of about a 30-m GIS section (on the load side of the disconnect) connected to a 0.75-km single-circuit overhead line. The line terminates at the station service transformer at Darlington NGS. Two sets of Capacitor Voltage Transformers (CVT) are connected at the GIS to overhead-line interface: one set for monitoring line voltages for protective relaying, and the second set for reducing the rate of rise of incident lightning surges. The CVTs are of relevance here only in that they introduce appreciable additional capacitance into the circuit, which increases the capacitive current required to be interrupted by the disconnect.

The station service transformers are 3-limbed core units, rated 500/13.8 kV, 80 MVA and connected in star configuration on both sides. The high-voltage winding neutral is solidly grounded. Further data concerning one of the units is given in Appendix A.

3. BASIS OF ANALYSIS

Since the intended application for this device is unique, a preliminary assessment of the likely operating performance was made iteratively on the basis of results of analytical studies and available information concerning the disconnect. Pertinent details concerning the device, which form the basis of our analysis, are summarized here.

The disconnect comprises three sets of high-speed contacts housed individually in conventional GIS enclosure and operated nominally at an SF6 gas pressure of 4.5 bar. The three phases are mechanically ganged through linkages, such that opening and closing operations are initiated simultaneously on all phases. However because of mechanical play in linkages, it is expected that the instant of contact part on an opening operation

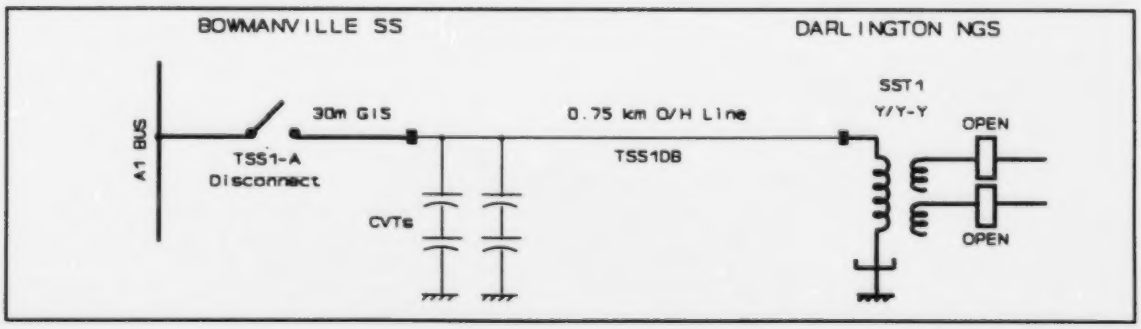

Figure 1: Single-line schematic of circuit supplying station service transformers at Darlington NGS.

could differ among phases by several power frequency cycles (termed inter-pole contact stagger). In comparison, contact stagger among circuit breaker poles is typically a small fraction of a power frequency cycle (1-2 ms).

Figure 2 depicts a simplified view of an opening operation, as inferred from discussions with Siemens. Starting from the closed position (Figure 2a), initiation of an opening operation causes the arcing contacts, consisting of a "catch-piece" (male contact) and a "contact-seat" (female contact), to be withdrawn from the left contact assembly (Figure 2b). Simultaneously, a spring-loaded mechanism is charged up in the left assembly for eventual retraction of the contact-seat. The arcing contacts eventually disengage (Figure 2c). The contact-seat retracts towards the left assembly under spring force, while the catch-piece continues towards the right assembly. The opening operation is complete in Figure 2d. To our knowledge, there is no provision for forced arc-cooling or arc-extension on an opening operation (e.g. by puffer action or gas blast). Contact separation in the fully open position is about 16 cm.

In order to predict the switching performance expected of this device, knowledge is required concerning its rate of dielectric strength recovery following arc extinction at the expected current levels. Since this information is not available, we have based our assessment on the withstand strength observed on closing operations (Figure 3)/8/[1]. Use of this data in place of the dielectric recovery envelope is expected to favour successful interruption in our analysis because dielectric recovery following arc extinction is hampered by thermal and ionization effects. This introduces some uncertainty in our assessment of the likely switching performance but does not alter the expected switching duty appreciably. Having recognized this limitation, we note from the withstand data that the dielectric strength for a 4 cm contact-gap is about 1.4 pu (500 kV base) of the line to ground

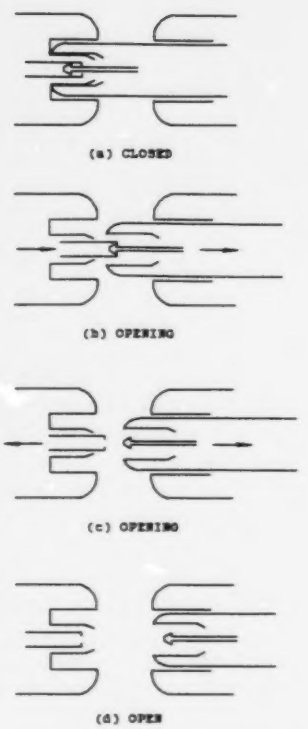

Figure 2: Simplified view of an opening operation on 500 kV disconnect.

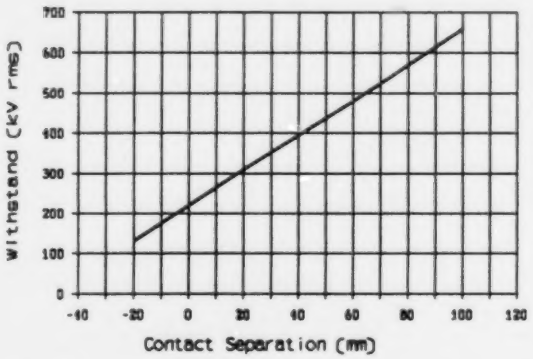

Figure 3: Contact gap withstand (at 4 bar) versus contact separation on closing operations.

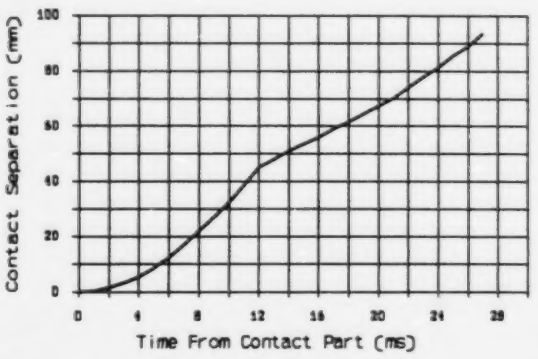

Figure 4: Contact separation as a function of duration from contact part.

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1 The plotted line delineates the approximate boundary below which no breakdowns were observed in closing operations. Contact separation is defined as the distance between the tips of current carrying contacts, measured along the axis of contact motion. This distance assumes negative values near the fully closed position because of the shoulder-sleeve contact mating arrangement.

voltage at SF6 gas pressure of 4 bar. This contact spacing is reached about 11 ms after contact separation (Figure 4), which is about the time when the spring-loaded female contact reaches its end of travel (about 12 ms). In our view this marks a significant event in the opening cycle since contact parting speed is reduced considerably beyond this instant. In addition, the dielectric strength at this gap spacing is well in excess of system voltage. Hence it could be reasoned that current ought to be interrupted by this time. On the other hand, perhaps allowance should also be made for thermal and ionization effects in the post-arc period (which are not accounted for in the withstand envelope of Figure 3), and this could extend the acceptable arcing duration somewhat. Continued arcing much beyond this duration would appear to be undesirable since it could increase the possibility of a fault occurring to the enclosure. On this basis, attention was focused on current interruption and the resultant electromagnetic transients within durations of up to two power-frequency cycles after contact part. Contact spacing at two cycles after contact part is about 10 cm.

4. ASSESSMENT OF EXPECTED SWITCHING PERFORMANCE

The predicted interrupting duties for first, second and third pole opening are given in Table I. Details of the analysis are given in Appendix B. A discussion of the findings follows.

The first pole to open is required to interrupt a line charging current of about 1.8 A (capacitive) at a system operating voltage of 550 kV. Magnetizing current drawn by the station service transformer is less than 10% of the line charging current, hence it is not a factor in this application. After current is interrupted in the first pole, line potentials remain balanced because of the three limbed transformer core construction (which has the same effect as presence of a delta connected winding). Consequently the Recovery Voltage (RV) is minimal, being about 0.03 pu at the power frequency. Even if the disconnect chops current at these low levels, the Transient Recovery Voltage (TRV) is less than 33 kV per ampere chopped at a frequency of about 350 Hz. In either case, the switching duty appears benign. Therefore first pole opening should be uneventful.

Table I
Expected Switching Duty During Disconnect Opening

	Pole 1 Opening	Pole 2 Opening	Pole 3 Opening
Power frequency current (A rms)	1.8	3.1	2.7
Power frequency recovery voltage (pu)	< 0.1	0.9	1.5
Transient recovery voltage following current chopping	33 kV/A at 350 Hz	Not applicable	7 kV/A at 680 Hz
Transient inrush current following transformer saturation (A peak)	Not applicable	Not applicable	20
Transient current following restrike (A peak)	Not applicable	10	20

After current has been interrupted in one phase, power-frequency current in the remaining phases increases to about 3.1 A rms because they supply line charging current for the open phase through the transformer. When current is interrupted in one of these phases, the TRV is primarily 60 Hz initially, tending towards 0.9 pu in one-quarter cycle. However before it reaches this peak, the transformer core saturates. The resulting voltage transients on the line increase the TRV across both open phases, possibly leading to a dielectric breakdown on the second pole. If a breakdown does occur, an inrush current transient is produced similar in nature to that encountered on energizing a transformer, though much lower in magnitude. Computer simulations show that this current could reach 10 A peak after a restrike[2], or possibly somewhat higher depending on the transformer magnetization characteristic. The disconnect could therefore be required to quench and successfully interrupt a 10 A arc. This clearly represents a more onerous duty than that contemplated originally.

Even if the second pole interrupts without restriking, saturation of the transformer core could produce inrush current approaching 20 A peak in the third phase and lasting several power frequency cycles. Unless contact-part on this pole happens to be delayed beyond several cycles, the disconnect will be required to interrupt this inrush current. If however contact-part is delayed favourably, the third pole will be required to interrupt about 2.7 A rms power frequency current. The recovery voltage is primarily 60 Hz, and limited by transformer saturation to about 1.5 pu. If the device chops current, a transient line-to-ground voltage approaching 7 kV per ampere of chopped current is expected at about 680 Hz.

The foregoing analysis suggests that the interrupting duty on second and third poles exceeds the specified levels, and is fundamentally different from that envisaged originally. At the same time there is no evidence that the disconnect is capable of this more severe duty. While we are unable to predict the switching performance with certainty, it seems possible that the higher current could prolong arcing durations on opening, possibly increasing the likelihood of a flashover to the enclosure. The manufacturer's opinion should be sought in view of the current analysis to establish if the disconnect is considered suitable for this application. Until reasonable evidence of the required switching capability is available, full-scale switching tests on site are not advisable.

5. SUMMARY

Analytical studies and computer simulations have been performed to predict the switching duty imposed on SF6 disconnects at Bowmanville SS when switching a station service transformer off-potential at Darlington NGS. The magnitude of power frequency current to be interrupted on first, second and third pole opening is 1.8 A, 3.1 A and 2.7 A rms respectively. However because of saturation of the transformer core during the staggered three-phase opening operation, the disconnect may be required to interrupt transformer inrush currents approaching 20 A peak. This represents a considerably more severe switching duty than that envisaged originally.

With the information available to us, we are unable to predict the switching performance of this disconnect with certainty. We are concerned however that prolonged arcing could occur across the opening contacts due to the higher current levels, and this could enhance the likelihood of a flashover to the enclosure (in GIS). Therefore application of this disconnect as originally intended is not advisable at this time.

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2 A breakdown across contact gap within 90 electrical degrees after initial current interruption is termed a reignition, after 90 degrees is a restrike.

6. RECOMMENDATIONS

Since we have no evidence that the disconnects provided at Bowmanville SS are capable of the expected switching duty, we recommend that full-scale switching tests not be conducted on site, and the switches not be used as originally intended. If however the intended application is considered an essential operating requirement, then suitable evidence should be sought from the manufacturer before tests are conducted on site.

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Submitted:

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AN:td

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5. A.L. Ing. Minutes of Meeting, "Bowmanville SS 500 kV SF6 Switchgear", April 17, 1986.

6. G. Luxa, A. Diessner. Memo to M.A. Machacek, "Bowmanville SS - 500 kV Switchgear Disconnect Switch", July 6, 1984.

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10. "ElectroMagnetic Transients Program (EMTP) User's Manual", Bonneville Power Administration, Revised March 1983.

APPENDIX A
EQUIPMENT INFORMATION

A.1 Station Service Transformer

Westinghouse Canada Inc. Serial No. A3S7946

Ratings: 500/13.8-13.8 kV, 80 MVA, Wye-grounded/Wye-Wye (reactor grounded)

Winding resistance:	HV	15.08 Ω
at 85°C	LV1	0.0184 Ω
on HV tap position 17	LV2	0.0179 Ω

No load loss at 100% rated voltage: 70 kW

Exciting Current:	0.146% at 90% rated voltage on 80 MVA base
	0.143% at 95%
	0.133% at 100%
	0.166% at 105%
	0.188% at 110%

Positive Sequence Impedance:	HV to LV1	19.3%
on 80 MVA base	HV to LV2	19.2%
	HV to (LV1+LV2)	10.1%
	LV1 to LV2	36.0%

Zero Sequence Impedance:	HV winding	56.5%
on 80 MVA base	LV1 windings	76.9%
	LV2 winding	77.1%

A.2 SF6 Disconnect

Siemens Type 8D.5

Rated voltage 550 kV/$\sqrt{3}$ = 318 kV

SF6 Pressure 4.5 bar (abs.)

Rated lightning impulse withstand voltage to earth 1550 kV

Rated switching impulse withstand voltage to earth 1250 kV

APPENDIX B
ANALYSIS OF EXPECTED SWITCHING DUTY

Analysis of the voltage and current transients resulting from individual breaker pole openings was carried out using classical symmetrical component networks, and confirmed by computer simulations using the ElectroMagnetic Transients Program (EMTP)/10/. Figure B-1 depicts the positive, negative and zero sequence networks for the system under study. Parameter values are as follows.

The capacitance of the 30-m GIS section is estimated as about 1.7 nF. Capacitance values for the 0.75-km overhead line are about 8 nF/phase positive sequence, 4 nF/phase zero sequence. The outdoor CVTs have a capacitance of about 5 nF/phase. Therefore the total capacitance is about 15 nF/phase positive sequence (C^+), 11 nF/phase zero sequence (C^0). Magnetizing inductance (L_m) for the SST is taken as 1000-3000 pu on rating (500 kV, 80 MVA), zero sequence inductance seen from the HV terminals (L^0) is quoted as about 60% on rating. Source inductance L_s, while shown in the figure, is small relative to transformer inductances and is of no consequence in the analysis.

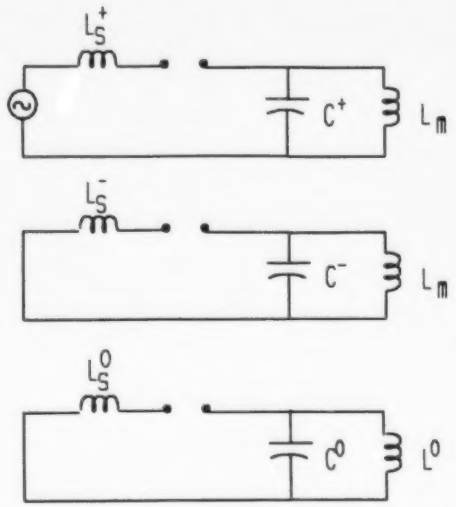

Figure B-1: Sequence networks for predicting the switching duty imposed on the disconnect.

B.1 First Pole Opening

The current to be interrupted under balanced conditions is primarily due to a 15 nF/phase capacitive load, or about 1.8 A rms at 550 kV operating voltage. Transformer magnetizing current is less than 0.1 A rms.

For first pole opening, the symmetrical component networks are connected in parallel when viewed from breaker terminals. The recovery voltage, either due to current chopping or normal clearing at current zero, is calculated by applying a suitable compensating current source across nodes corresponding to the breaker terminals. For a current chop, a step current source of magnitude equal to the chopped current is applied. The resulting recovery voltage is three times the voltage developed across the step source (ie. three times any one of the sequence voltages, by transformation of symmetrical component quantities to phase domain quantities). Neglecting damping, the peak recovery voltage is approximately

$$3\, I_c \left[\frac{L^0}{2C^+ + C^0}\right]^{1/2} \quad \text{(V/A)}$$

where I_c is the magnitude of current chopped. Substituting L^0 = 5 H, C^+ = 15 nF, C^0 = 11 nF, and I_c = 1 A gives a recovery voltage of 33 kV per ampere of chopped current.

The frequency of the recovery voltage corresponds to the natural frequency of the circuit:

$$\frac{1}{2\pi\, [L^0\,(2C^+ + C^0)]\,1/2} \quad \text{(Hz)}$$

or about 350 Hz using the numerical values used earlier.

The power frequency component of recovery voltage is computed by applying a 60 Hz compensating current source of magnitude equal to the load current. After transformation to phase domain quantities, its magnitude is approximately

$$360\ \pi\ L^{o}\ I_L \qquad (V)$$

with I_L being the magnitude of power frequency current interrupted. Interruption of 1.8 A rms therefore produces a power frequency recovery voltage of about 10 kV or about 0.03 pu of the line-to-ground voltage.

B.2 Second Pole Opening

The power-frequency current remaining in the two closed phases is determined from a parallel connection of symmetrical component networks driven by a 60 Hz positive sequence source. This gives a current of about $\sqrt{3}$ times that under balanced conditions, or about 3.1 A rms. The disconnect is not likely to chop current at these levels, therefore interruption is assumed to occur at a current zero crossing, perhaps several power frequency cycles after first pole interruption.

After current is interrupted in the second phase, the recovery voltage across both open poles is initially 60 Hz, increasing towards 0.9 pu in one-quarter power frequency cycle. At some point during this period, the transformer saturates as evidenced by inrush current in the conducting phase in EMTP simulations (Figure B-2). This increases the transient recovery voltage across the opening pole (Figure B-3), possibly causing a reignition or a restrike. A restrike appears possible on the basis of available data, which shows for instance that 8.5 ms after contact separation, contact spacing is about 25 mm corresponding to a withstand level near 1 pu. This withstand level is approached in EMTP simulations within the designated period if contact part is assumed to occur near the current zero crossing. A restrike results in transformer inrush currents approaching 10 A peak (Figure B-4).

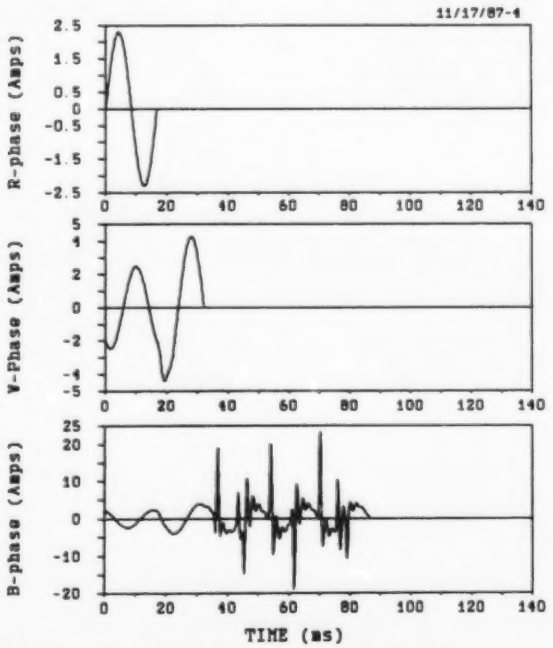

Figure B-2: Inrush current in B-phase after R-phase and W-phase have interrupted current.

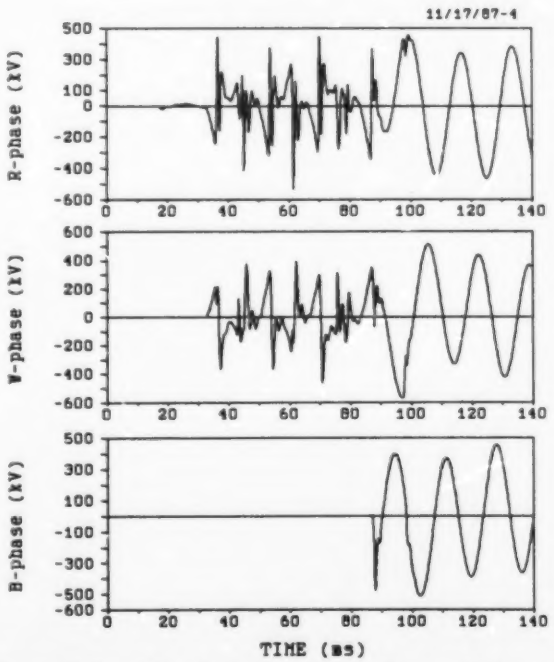

Figure B-3: Transient recovery voltages during a sequential R,W,B-phase opening operation.

B.3 Third Pole Opening

After the second pole has cleared, the power frequency current to be interrupted is about 50% higher per phase than that under balanced conditions, as determined from a series connection of symmetrical component networks. The current to be interrupted is therefore about 2.7 A rms. If current chopping occurs, the recovery voltage per ampere of current chopped approaches

$$\frac{I_c}{3}\left(\frac{L^o}{C^o}\right)^{1/2} \quad \text{(V/A)}$$

Note that the magnitude of the compensating current source in this case is one-third the magnitude of the current chopped (by transformation of the phase domain current to its sequence components). The frequency of the recovery voltage transient is

$$\frac{1}{2\pi\,(L^o\,C^o)^{1/2}} \quad \text{(Hz)}$$

For Bowmanville SS, these correspond to 7 kV per ampere and 680 Hz respectively.

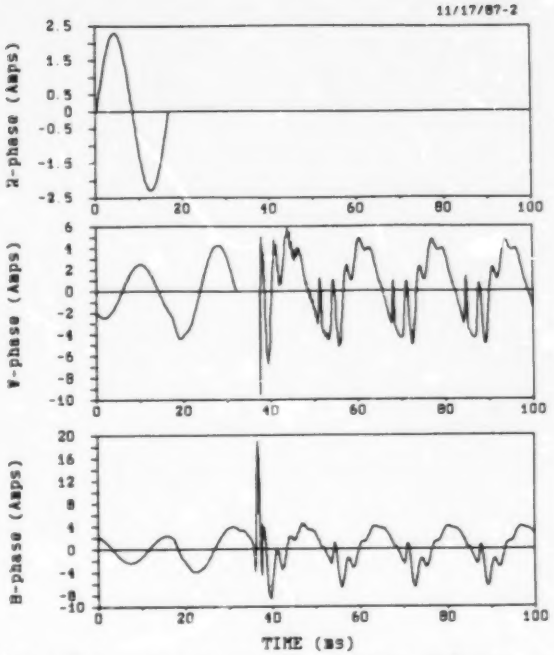

Figure B-4: Inrush current transient following a restrike on the second phase to open (W-phase).

A more severe interrupting duty is possible on this pole due to transformer saturation following second pole opening (Figure B-2), or due to a restrike on the second pole (Figure B-4). In both cases, an inrush current approaching 20 A and lasting several power frequency cycles could result on this phase. Since it is possible that third pole opening could coincide with the presence of this inrush current, the disconnect may be required to interrupt such current transients.